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Fundamental physics possibilities at the European Spallation Source

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Abstract. The construction of the European Spallation has recently started in Lund, Sweden. In addition to the neutron scattering instruments the ESS is designed to serve, the construction of a new spallation source opens up new possibilities for fundamental physics experiments. In this paper some of the possibilities for in-pile experiments are discussed, i.e. experiments that impacts the target-moderator-reflector systems and that can best be constructed if they are considered already in the design phase of a new facility. The main focus of the work reported here is put on possible changes to the baseline target-moderator-reflector design that would allow for ultra cold neutron production and extraction. For completeness, the paper also discuss possible discovery physics experiments that are presently being studied in the framework of ESS. In parallel to the topics discussed here, work is ongoing investigating the scientific potential for in-beam fundamental physics experiments at the ESS.

1. Introduction

In this paper several possibilities for fundamental physics at the ESS are discussed. First, and in greatest detail, the concept of a through-going beam-tube is discussed (Section 2). The impact on existing cold/thermal beam-lines is quantified and the heat-load of a candidate ultra cold neutron (UCN) moderator placed in the through-going tube is calculated. Aiming at providing an overview of ongoing efforts, other novel ideas for UCN moderators are briefly presented in Section 3: A voluminous liquid D_2 moderator, an in-pile solid D_2 as well a satellite methane moderator.

Finally in Section 4 the possibilities of discovery physics at the ESS are discussed, in particular the searches for neutron-anti-neutron oscillations and dark photons.

2. Through-going tube

The possibilities for installing a UCN moderator at the ESS strongly depend on the layout of the target-moderator-reflector. In figure 1 the central parts of the target-moderator-reflector are shown according to the baseline design of the Technical Design Report [1]. In this scenario, voluminous para-hydrogen moderators (two cylinders of 16 cm diameter, 13 cm high) are situated on each side of the target, and thus close to the spallation hot-spot. The introduction of a UCN moderator would have to stay clear of the two existing moderators - for example by placing it in a through-going tube underneath the lower para-hydrogen moderator. As the main focus of

the ESS facility is that of providing cold and thermal neutrons, it is essential when evaluating possible changes to the baseline design to monitor the performance impact on the cold/thermal neutrons available at the instrument beam-lines. Therefore, a study was carried out monitoring the flux available for UCN moderation versus the impact on neutron flux in the cold/thermal beam-lines - for different vertical positions of the through-going tube.

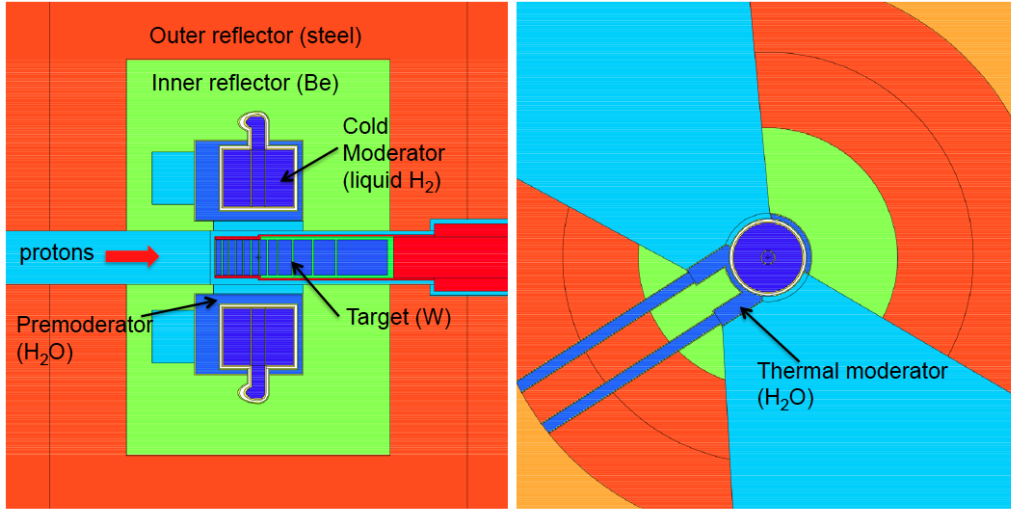


Figure 1. Vertical (left) and horizontal (right) cross section of the target-moderator-reflector geometry in the Technical Design Report [1].

2.1. Simulation setup

Based on the baseline MCNPX[2, 3] model used for the neutronics calculations of the ESS Technical Design Report (TDR)[1], a 25 cm×25 cm tube is defined. To best avoid the dominantly forward directed high energy shower particles from the proton beam impacting the target wheel, while obtaining maximal thermal flux, the tube is centered around and parallel to the x -axis (ie. perpendicular to the proton beam). The tube is centered at $z = 0$ while the y coordinate (the 'depth' under the proton beam) is left free and various possibilities are studied: $y \in [-47.5; -62.5]$ cm (central in tube)¹. Figure 2 shows an example in which the void volume (the UCN through-going tube) replaces parts of the beryllium inner reflector (red), but more severely impacts the outer reflector (orange).

To measure the possible impact on cold/thermal beam lines, eight representative point detectors are placed in the beam-ports at the boundary of the Target-Moderator-Reflector(TMR) plug, corresponding to the blue stars on the lower right insert of figure 2.

2.2. Results

Comparing flux ratios between modified (i.e. including UCN tube) and baseline design, in the three energy bins (cold, intermediate and thermal) show that regardless of the position of through-going tube, the upper beam-lines are unaffected.

¹ The coordinate system used at the ESS is right-handed, with the protons travelling along the z -axis, impacting the target in the origin. The y -axis is positive upwards (i.e. opposite gravity).

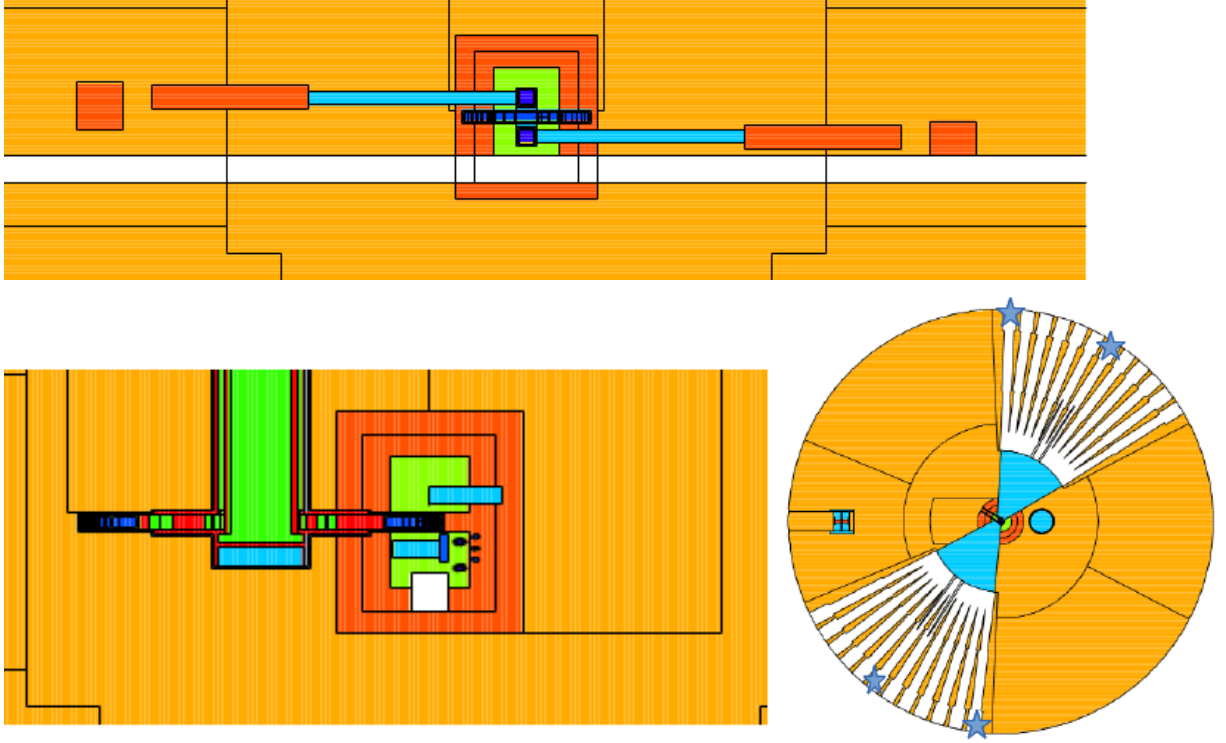


Figure 2. Geometry of the target, moderator and reflector showing the UCN through-going tube (white areas in upper and lower left-hand inserts) placed at $y = -47.5$ cm (central), corresponding to the topmost of the studied geometries. The blue stars in the lower right-hand insert shows the position of the lower point detectors. Note that the xz -plane (lower right-hand insert) is cut at $y = -18$ cm, wherefore the UCN tube is not visible.

y position [cm]	Flux [n/s/cm ²]	Heat-load [W/cm ³]
-47.5	2.4×10^{13}	0.20
-55.0	1.3×10^{13}	0.11
-62.5	2.9×10^{12}	0.06

Table 1. Flux and heat-load at different y -positions (central) of the through-going tube.

Furthermore, the impact does not fluctuate significantly between the four lower tally positions: Therefore the response of all lower tallies are collapsed to one average for each position of the through-going tube.

Finally, the relation between the impact in terms of relative decrease in available cold/thermal flux at the cold/thermal instruments versus the (central) flux available for UCN production is shown in figure 3. It can be concluded that in the baseline configuration of the ESS TMR, a through-going tube can be introduced with insignificant impact on the cold/thermal beam-lines. In the through-going tube a flux of up to 2×10^{13} n/cm²/s can be reached. The results are summarised in table 1, along with the heat-load results based on inserting a dummy $16\text{cm} \times 16\text{cm} \times 16\text{cm}$ para-hydrogen central in the tube.

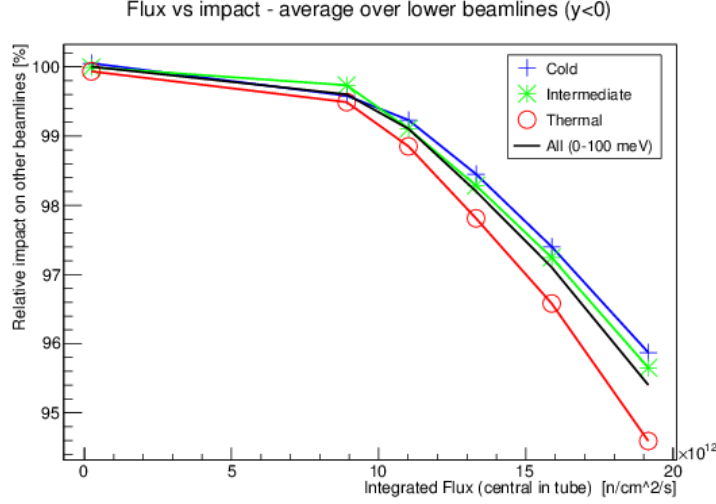


Figure 3. Relation between cold, intermediate and thermal flux in the lower cold/thermal beam-lines versus the flux available for UCN, central in the through-going tube. The black curve shows the average between the cold, intermediate and thermal curves. Each point corresponds to a specific vertical position of the through-going tube.

Heat-load [mW/cm ³]	Flux [0-5]meV [n/cm ² /s]	Flux [5-20]meV [n/cm ² /s]	Flux [20-100]meV [n/cm ² /s]
2.5	3.8·10 ¹²	9.0·10 ¹²	1.8·10 ¹²

Table 2. Heat-load on cryogenic ⁴He and integrated cold/intermediate/thermal flux for the ESS implementation of Golub’s UCN design discussed in the text, and shown in figure 4. The results are obtained from a MCNPX simulation - the relative statistical uncertainties are ~0.1%.

2.3. ⁴He UCN moderator according to Golub’s design

Taking into account Carnot efficiency of cooling at cryogenic temperatures as would be required for a UCN moderator, the heat-loads of table 1 are problematic. Inspired from work of Golub and collaborators [4] that faced similar difficulties, the design shown in figure 4 is considered. Here, bismuth’s ability to shield against gammas and filter neutrons is exploited. The corresponding heat-load and flux in the cryogenic volume is shown in table 2.

In [5] Golub and co-authors provide a scheme, for calculating maximum UCN production in a ⁴He moderator, given an incoming cold/thermal spectrum and integrated flux. Inserting the values of table 2 and the observed spectrum, one arrives at a total maximal UCN production rate in 30 cm × 30 cm × 30 cm ⁴He to be 1.5·10⁸ UCN/s. It should be stressed that this is the maximum production rate, and it does not take into account any of the challenges confronted when attempting to store, extract or handle the UCN’s. In addition, the design discussed here does not allow for two cold/thermal moderators at ESS is therefore not a viable option for ESS. Once the layout of the cold and thermal moderators have been decided, the study of the possibility to add a UCN moderator, will need to be revisited.

3. Other ideas for UCN moderators

3.1. Voluminous D₂ moderator

To facilitate experiments depending on the total number of neutrons in a sizable beam, the option of a voluminous D₂ moderator, in a large cross-section extraction guide is discussed and

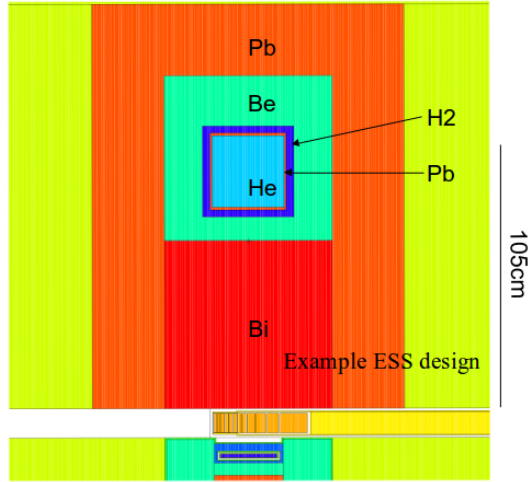


Figure 4. Possible design of an in-pile ^4He moderator at ESS - inspired from Golub [4].

its neutronic performance has been investigated. Under the assumption, that the scattering instruments at the ESS are served by a single moderator above the target, the performance of a $25\text{ cm} \times 25\text{ cm} \times 20.6\text{ cm}$ rectangular D_2 moderator placed in a through-going beam-tube under the target has been studied. The results of this feasibility study show that at least 3-4 times cold neutron beam intensity could be accomplished with respect to what would be available from a TDR configuration (figure 1). For details, the reader is referred to [6].

3.2. Satellite ^4He moderator

In figure 5(left) the ^4He *satellite* is sketched as suggested by E. Lychagin and collaborators.

The basic idea is to move the UCN moderator to a distance where the heating is manageable. When this is combined with the exclusive use of low neutron capture materials, a very high UCN density can be achieved even at a significant distance to the spallation target. The viewed surface of the cold (or thermal) moderator, and thus the size of the moderator, is a limiting parameter. For more details see [7].

3.3. D_2 pump

In this design, proposed by V. Nesvizhevsky, some of the characteristics of the 2 GeV long pulse proton driver at the ESS are exploited. An ultra-cold (few K) solid deuterium moderator ($\sim 1\text{ cm}$ thick) is installed close to the spallation target, and is fed by a large liquid deuterium moderator.

During the duration of the pulse: 2.5 ms, the UCN will move $\sim 0.5\text{ cm}$ (at $\sim 4\text{ m/s}$), thus filling the *halo* in front of the D_2 . During the time between pulses, a membrane slowly push the UCN back away from the D_2 , after which it rapidly moves back to the D_2 , ready for the next pulse. The configuration is sketched in figure 5(right) - for details see [8].

4. Potential for discovery physics at ESS

The lack of discoveries at accelerators exploring the high energy frontier strengthens the motivation search of new physics elsewhere. The unprecedented proton beam power of 5 MW expected at the ESS pose unique possibilities to search for new physics, including the searches for $n\bar{n}$ oscillations and Dark Photons briefly discussed below.

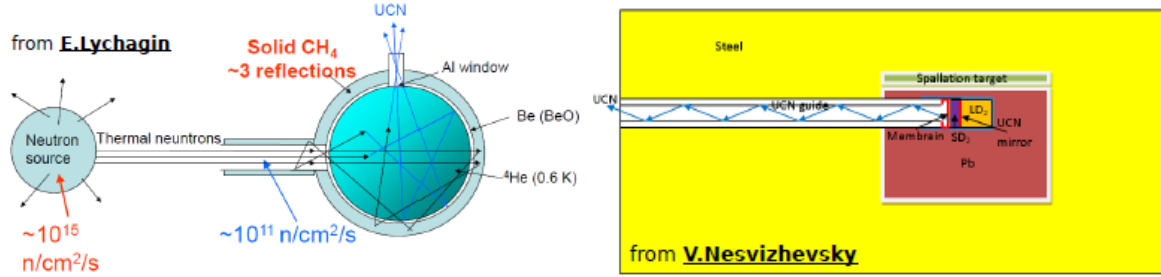


Figure 5. Sketches of the Satellite ⁴He moderator (left) and D₂ pump (right) as referred to in the text.

4.1. Search for $n\bar{n}$ oscillations

Deviations from baryon number conservation have not been observed, but yet the Universe consists of baryons rather than anti-baryons. It is an intriguing question, to explain how the asymmetry came to be. Also, to explain that neutrinos are light, interactions with lepton number violation with $\Delta L=2$ are needed. If quarks and leptons are unified at some scale, $\Delta L = 2 \Leftrightarrow \Delta B = 2$, ie. $n\bar{n}$ oscillations could then be a consequence of GUT theories for neutrino masses. If neutrons can oscillate to anti-neutrons, the probability would be proportional to the flight time squared, so an experiment to search for $n\bar{n}$ oscillations would aim for highest possible flight time, which would require an intense cold neutrons beam and good vacuum. To observe the anti-neutrons, and annihilation target (film) is needed and it should be surrounded by detectors in a magnetic field to track the produced charged pions and calorimeters to perform energy measurement of the neutron pions. By this approach the invariant mass of the annihilating particle can be reconstructed offline and background can be severely suppressed. Since this would be a discovery type of experiment background suppression is essential since any presence of background at all would reduce the sensitivity. The present limit: $\tau > 0.87 \times 10^8$ s was set by ILL experiment [9], using an approach according to lines ideas suggested here. However, partly due to the fact that the the experiment was built at an existing facility it suffered from a number of constraints - some of which can be avoided by planning the experiment while the facility is being designed. Presently an $n\bar{n}$ collaboration being formed with the intention to propose a $n\bar{n}$ experiment at ESS. Initial calculations suggest that the sensitivity could be at least two orders of magnitude better that what was reached at the ILL experiment.

4.2. Search for Dark Photons

The expectation that ESS will set a world record in beam power makes it an excellent place to look for new physics that couples to Standard Model particles, but is suppressed, and therefore escaped detection at colliders due to a low production rate. Examples include dark matter candidates such as dark photons [11] - particles coupling (slightly) to photons in the presence of matter. If such particles would exist they could possibly be produced in the harsh radiation environment of the ESS target. Once produced, they could escape through the shielding. By placing a calorimeter along the proton beam direction downstream from the target (on the backside of the shielding) one could search for dark photons converted back to photons in (or immediately before) the calorimeter. Such particles would appear as a excess of events (a peak) in the observed spectrum, corresponding to the given dark photon mass. Dark photons has been searched for using similar approaches in the past - the present limits are based on samples up to 10^{19} protons on target are shown in figure 6.

At ESS 10^{23} protons on target is expected yearly - a feasibility study investigating the ESS sensitivity for dark photon search is foreseen.

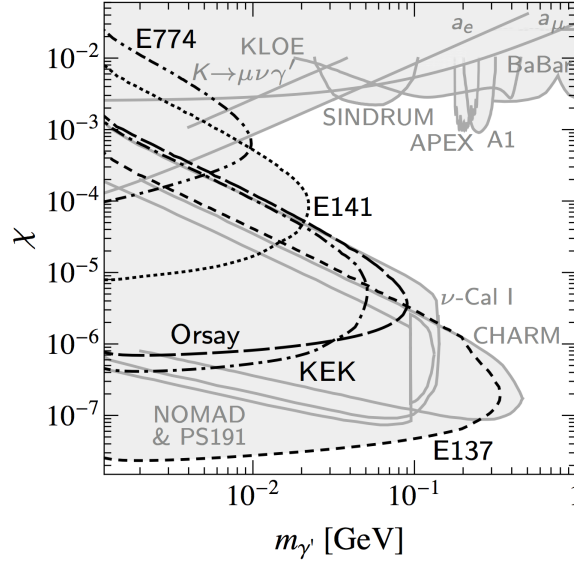


Figure 6. Present limits of of dark photon searches in the parameter space of the coupling strength, χ and dark photon mass $m_{\gamma'}$. The figure is due to S. Andreas [10].

5. Acknowledgements

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